Submitted to *Geophysical Research Letters*, 2000.

Non-Adiabatic Response of Relativistic Radiation Belt Electrons to GEM magnetic storms

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Abstract. The importance of fully adiabatic effects in the relativistic radiation belt electron response to magnetic storms is poorly characterized due to many difficulties in calculating adiabatic flux response. Using the adiabatic flux model of *Kim and Chan* [1997a] and Los Alamos National Laboratory geosynchronous satellite data, we examine the relative timing of the adiabatic and non-adiabatic flux responses. In the three storms identified by the GEM community for in depth study, the non-adiabatic energization occurs hours earlier than the adiabatic re-energization. The adiabatic energization can account for only 10-20% of the flux increases in the first recovery stages, and only 1% of the flux increase if there is continuing activity.

1. Introduction

Relativistic electron ($E > 1$ MeV) populations in the radiation belts are sensitive to magnetic disturbances including solar coronal mass ejections (CME's) [*Baker et al.*, 1998] and recurrent high speed solar wind streams [*Paulikas and Blake*, 1979]. During magnetic storms there is usually a sudden decrease in relativistic electron flux followed by a slower increase. The increase in the fixed energy electron flux can take from 1-5 days to peak depending on L-shell and the individual storm behavior. The flux decrease is frequently attributed to the "Dst effect", in which electrons move outward in order to conserve their adiabatic invariants as the magnetic field decreases. If only the adiabatic response is considered the flux response is as follows: The increase in the ring current associated with the Dst drop decreases the magnetic field in the inner magnetosphere; in order to conserve the third adiabatic invariant, the electrons move outward. By moving outward, the electrons are now in a lower magnetic field and thus lose energy in order to conserve their first adiabatic invariant. For a fixed energy detector, a drop in the flux is observed as the electrons move outward and decrease in energy. As the Dst recovers and the magnetic field returns to the initial conditions, the electrons return to their original position and energy level. However, observations of the relativistic electrons show that processes other than the adiabatic response must be involved as the electron fluxes increase to levels above the pre-storm level (e.g.,*Nagai* [1998]). *Kim and Chan* [1997a] determined the energization due to adiabatic effects using a fully adiabatic model, and found that in the November 2, 1993, storm most of the flux decrease could be accounted for by fully adiabatic effects while the increase was not accounted for by the adiabatic response.

Several theories seek to explain the flux increases seen during recovery. These include energization by magnetic pumping/recirculation using several different methods to scatter and move the particles [*Nishida*, 1976; *Fujimoto and Nishida*, 1990; *Liu et al.*, 1999]. Direct heating of the electrons by ULF wave interactions has been invoked by *Elkington et al.* [1999] and *Hudson et al.* [1999]. Whistler mode wave interactions with electrons near the plasmapause have also been proposed [*Abel and Thorne*, 1998a, b; *Boscher et al.*, 2000].

One of the outstanding questions is the relative timing when adiabatic effects become less important than non-adiabatic energization process in explaining the relativistic electron flux increases. Several of the above theories require an extended period of time to energize the electrons. Therefore, the time scale of these processes is important.

The U.S. National Science Foundation's Geospace Environment Modeling (GEM) program has identified three CME related magnetic storms for in-depth study and comparison [*McAdams et al.*, 2001, in press]. The storms are May 15, 1997; September 25, 1998; and October 20, 1998. We look at the relativistic electron response to these storms at geosynchronous orbit ($R = 6.6\ R_e$) and compare adiabatic and observed flux responses using the *Kim and Chan* [1997a] model.

2. Electron Fluxes

For all three storms we use observations from the Los Alamos National Laboratory (LANL) geosynchronous satellites 1994-084, 1991-080 and 1990-095. We used electron flux data from the 1.8-3.5 MeV electron channel on the ESP instrument [*Meier et al.*, 1996]. The data were binned by 1 hour time increments to be consistent with the 1-hour Dst index data. The measurements from all three satellites in a given 1-hour bin were also averaged together to reduce variation due to the positions of the satellites in local time. While the averaging does reduce the local time dependence it does not eliminate it. This is particularly true when data from 1990-095 are unavailable since 1994-084 and 1991-080 are separated by only a few hours in local time.

We obtain a proxy for the fully adiabatic fluxes using the method of *Kim and Chan* [1997a] in which they derive the adiabatic storm-time electron flux from the pre-storm flux level at L=6.6 as a function of the Dst index. Although they report calculations done with several magnetic field models, we use only the Hilmer-Voight ring current field model [*Hilmer and Voight*, 1995]. We have extended the Kim-Chan model to fit $Dst < -100$ nT, which may introduce some error when Dst is highly disturbed since the field model was developed for $Dst > -100$. Nonetheless, we believe that even with some error in the model, the temporal evolution and the rough scale of the fluxes at $Dst < -100$ provides useful physical insight.

For each storm, we take the first 6 hours shown in Figure 1 as the "pre-storm" flux level. In order to find the initial flux level (flux when $Dst = 0$), we use the average Dst value for the first 6 hours shown in Figure 1 for each storm and the average measured LANL flux level for that period and extrapolate the flux level for $Dst = 0$ for each storm. Then we calculate the "adiabatic" fluxes as a function of Dst, normalized by the initial flux level.

Figure 1 compares the predicted adiabatic fluxes to the LANL observed fluxes for the three storms. The red curve is the adiabatic flux, the green curve is the average measured LANL flux and the black curve shows the ratio of LANL to predicted adiabatic fluxes. The same numeric scale suffices for both the ratio and flux levels in this figure.

3. Results

Comparing the observed electron fluxes with the calculated fully adiabatic fluxes allows us to examine the timing of the adiabatic changes relative to the observed flux decrease and increase associated with storm main phase. In May 1997 (Figure 1a), there is no detectable delay between the inflection point of the predicted adiabatic fluxes and the inflection point of the LANL fluxes, however, the measured LANL fluxes increase much more rapidly than the predicted adiabatic fluxes.

In September 1998 (Figure 1b), the predicted adiabatic fluxes begin to rise 4-5 hours later than the measured LANL fluxes. The ratio between the LANL and predicted adiabatic fluxes goes above 1 at nearly the same time that the dropout begins and approximately 4 hours before the Dst minimum. Therefore, although the fluxes are decreasing, they are decreasing less quickly than expected based on the adiabatic prediction. (We note that the large variations in the measured fluxes, and therefore the ratios, prior to the flux dropout are due to local time effects when data was primarily available from satellites on the nightside where tail thinning can cause additional dynamics.)

October 1998 (Figure 1c) shows the most striking example of delay in the adiabatic response. The measured LANL fluxes begin to rise approximately 16 hours before the predicted adiabatic fluxes. This large time delay may be related to the long storm main phase where the Dst depression lasted more than a day. The ratio increases to greater than 1 only 7-8 hours before the adiabatic fluxes begin to rise. The October 1998 storm is also different from the other two storms studied here in that the measured fluxes begin to decrease approximately 8 hours before the predicted adiabatic decrease. This decrease is likely due to either a local reconfiguration of the tail field (as with the fluctuations prior to storm onset in September 1998) or possibly to non-adiabatic loss processes which cause an actual loss of particles from the radiation belts prior to the build-up of the ring current.

Although the exact flux levels for the predicted adiabatic fluxes are somewhat unreliable during the storm main phase when $Dst < -100$ nT, a comparison of the levels of electron flux expected from a fully adiabatic response to the observed fluxes is useful. In May 1997, the smallest storm, the Dst minimum was near -135 nT. In

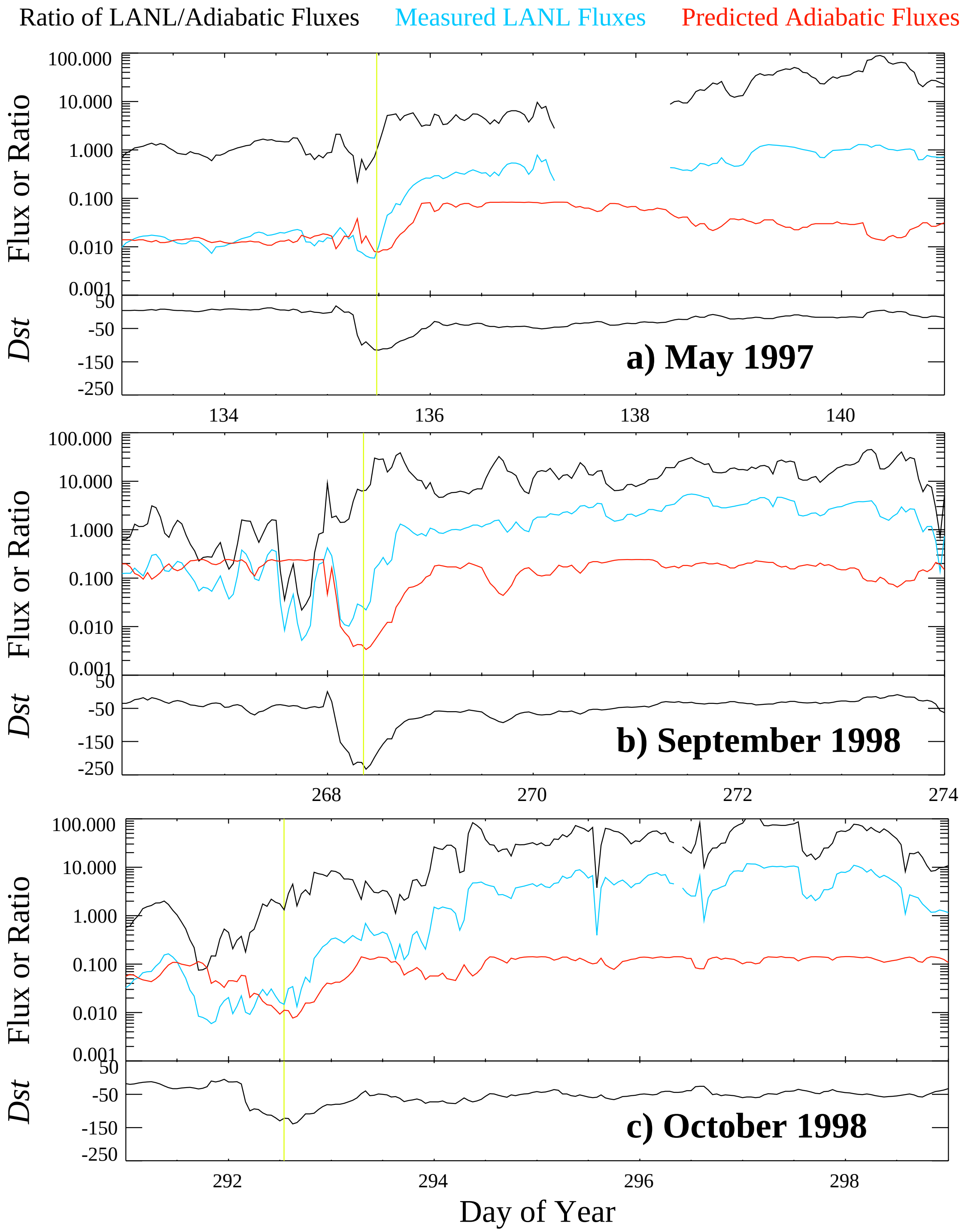

Figure 1. Flux comparisons from three GEM storms: In each panel, the red curve represents predicted adiabatic fluxes derived from *Dst*, the green curve shows the measured LANL 1.8 MeV electron fluxes, and the black curve shows the ratio of measured LANL to predicted adiabatic fluxes. The yellow line indicates when the *Dst* minimum occurs. a) May 15, 1997. b) September 25, 1998. c) October 1998.

this storm, the two flux levels are very close during the decrease, but during the recovery phase the measured LANL fluxes are approximately four times larger than the predicted adiabatic fluxes. September 1998 was the largest storm in terms of Dst minimum (-250 nT). In this storm, the difference in the minimum fluxes during main phase was approximately a factor of 3 with the measured LANL fluxes higher than the predicted adiabatic fluxes. During recovery the LANL/adiabatic ratio fluctuates but is near 10, implying that the adiabatic rebound accounts for only 10% of the post-storm electron fluxes. October 1998 has a more complicated profile in terms of the observed/predicted adiabatic flux ratio. The minimum fluxes reached by LANL and predicted adiabatic fluxes were very similar. After the first fast recovery (near day 293.3), the measured LANL fluxes were about 4 times larger than the predicted adiabatic fluxes. As the recovery progressed, the measured LANL fluxes continued to increase while the predicted adiabatic fluxes remained nearly the same with a slight dip near day 294. At the peak of the measured LANL fluxes (approximately day 296-297) the ratio between the two fluxes neared 100.

4. Conclusions

We have investigated the relationship between the fluxes of relativistic electrons measured at geosynchronous orbit with the fluxes predicted based on the fully adiabatic calculations of *Kim and Chan* [1997b]. We find that both the measured fluxes and the adiabatic predictions begin to decrease simultaneously. Since the adiabatic predictions are based only on the response to the ring current it appears that the so-called Dst effect is responsible for at least the timing of the relativistic electron dropout. However, the rate of decrease of the measured fluxes tends to be slower than predicted based on the adiabatic response and the ratio of the measured to predicted fluxes can increase above one, even as the dropout is intensifying.

This implies that there is some non-adiabatic energization of the fluxes that occurs simultaneously with the adiabatic de-energization due to the Dst effect. Since the measured fluxes are decreasing during the storm main phase the adiabatic effects must be stronger than any non-adiabatic energization that is taking place at that time. Nevertheless the timing is significant for understanding the relativistic energization process.

We note that there are a number of other processes that can contribute to the dropout of relativistic electrons during the main phase of a storm. Electrons can be lost to the magnetopause (sometimes called magnetopause shadowing), or they can be precipitated into the atmosphere through pitch angle scattering. Both of these processes have been observed but are not included in our analysis. We note though, that any loss processes will add to the adiabatic Dst effect and cause a larger dropout of the relativistic electron fluxes than predicted by the *Kim and Chan* [1997a] model. If loss processes dominated then the ratio between the measured and predicted fluxes would decrease below one as a result. Therefore if loss processes are significant during the storms analyzed in this study the apparent effects of the as yet undetermined source of non-adiabatic energization must be even larger. We further note that our conclusions are specific to geosynchronous orbit were we have made our measurements and where the *Kim and Chan* [1997a] model applies. Some storms can produce a persistent decrease at, for example, L=4 or 5 which implies that losses dominate at those L-shells for those storms. That was not the case for the GEM storms [*McAdams et al.*, 2001, in press].

In May 1997 and September 1998, the adiabatic re-energization in the recovery phase of the storm can account for approximately 10-20% of the total observed electron flux. In the initial recovery of the October 1998 storm, adiabatic increases can account for a similar amount of the observed fluxes. During the later recovery of October 1998, the measured LANL fluxes increase while the predicted adiabatic fluxes remain constant and the adiabatic portion accounts for only 1% of the observed flux. This may be related to the continuing Geomagnetic activity seen during this time. In two of the storms it appears that there is a single level of non-adiabatic flux increase which continues for the duration of the storm, while in October 1998, a second, non-adiabatic increase occurs after the initial storm recovery.

In these three storms we have shown that there is a large contribution from non-adiabatic processes to the energization of the radiation belt electrons during the main phase of geomagnetic storms. These processes appear to be active during the main phase and before the adiabatic processes re-energize the particles after the Dst minimum as well as during the recovery phase. In storms where there is continuing magnetic and auroral activity the non-adiabatic process may play a larger role than in storms with little post-main phase activity.

Acknowledgments.

We wish to thank R. Friedel for useful discussions and assistance in preparing the manuscript.

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Received July 6, 2000; revised January 9, 2001; accepted January 11, 2001.

This preprint was prepared with AGU's LaTeX macros v5.01, with the extension package 'AGU^{++}' by P. W. Daly, version 1.6b from 1999/08/19.